Optical Position Feedback and Phase Control of resonant 1D and 2D MOEMS-Scanners

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ABSTRACT

Resonantly driven oscillating MOEMS mirrors have many applications in the fields of optics, telecommunication and spectroscopy. Assuring stable resonant oscillation with well controlled amplitude under varying environmental conditions is a complex task, which can impede or retard incorporation of such MOEMS mirrors in large systems. For this we have developed compact modules comprising optical position sensing and driver electronics with closed loop control, which can ensure stable resonant operation of 1D and 2D micro-mirrors. In this contribution we present in much detail the position encoding and feedback scheme, and show very first experimental results with the novel 2D device.

Keywords: MOEMS, scanner mirror, closed loop, optical feedback, position sensing, electrostatic driving

1. INTRODUCTION

MOEMS scanner mirrors are of importance in various fields in optics, telecommunications and spectroscopy. They gain more and more importance to satisfy the industry demands for light-weight, miniaturizable, and cheap solutions for many opto-mechanical applications. Among others, micromechanical resonantly driven scanning mirrors like the ones shown in Fig. 1 are used in bar-code scanners¹, miniaturized spectrometers², light barriers³, and other applications. 2D-scanning mirrors are at the core of different projection applications^{4,5,6}.

Resonant driving of scanning mirrors has several advantages, including high mirror deflection angles, which can be obtained at relatively low driving voltages and with minimal energy consumption. Due to their small weight they are shock and vibration resistant and can feature high scanning rates (up to 30 kHz). Finally the small device dimensions and possible low production costs are important features with regard to mass production. On the other hand, they can only be driven with a sinusoidal trajectory, thus the projection patterns for the 2D scanners are limited to Lissajous-type figures. Furthermore there is no inherent position feedback of the movement of the mirror.

We have developed a compact device comprising optical position sensing, and driver electronics, with closed loop control, capable of driving resonant MOEMS micro-mirrors^{7,8}. The approach, based on adjusting the driving frequency to minimize the phase offset of the mirror oscillation, is very flexible and especially applicable for high frequency devices, where synchronized excitation⁹ is difficult. Very recently, we extended our approach to 2D scanner mirrors, which significantly increases the complexity of the device. In the following we will shortly recapitulate the position sensing scheme implemented in our devices, highlighting relevant issues with regard to the novel 2D device, and subsequently, in much detail, focus on the implementation and our most recent characterization results.

2. BASICS

2.1 electrostatically driven MOEMS scanners

Micromechanical scanner mirrors, as the ones shown in Fig. 1, are fabricated at the Fraunhofer IPMS using CMOS compatible technology¹⁰.

The 1D-mirrors consist of a plate suspended by two torsional springs and two comb like driving electrodes. In the 2-D mirrors the inner frame is further suspended by orthogonal springs and driven by another pair of electrodes. The vertical

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sides of the electrodes and the mirror plate form a variable capacitance C which is decreasing with increasing deflection angle ϕ of the plate. A voltage generates an electrostatic torque which accelerates the plate towards its rest position $\phi=0$ of the oscillation¹¹.

Fig. 1. Phase (i) and Amplitude (ii) as a function of frequency close to resonance for a MOEMS mirror at two different temperatures. Insets above shows the layout of a 1D- and a 2D MEMS scanner,

When driving with a fixed driving frequency the mirror will oscillate with half this frequency. In general, there will be an offset in the timing of the zero-deflection point with regard to the switching off of the driving voltage and only in the case that the mirror is driven exactly at its resonance frequency this phase is zero. However possible changes in the resonance frequency, which might occur due to environmental influences, can lead to suboptimal performance or the break-down of the oscillation. A possibility to overcome this problem is to measure the phase and actively adjust the driving frequency, which is the approach we implemented in our devices.

2.2 Position encoding scheme

Position encoding of the mirror movement is an important aspect for many applications. The capacitance variance can be used to detect the zero-transition and estimate the speed and amplitude of resonant MOEMS mirrors⁹. This was demonstrated using an especially designed integrated circuit and a 250 Hz mirror. However the capacitance signal is very weak and optical detection techniques promise higher accuracy. Another approach consists in the fabrication of piezoresistive areas on the springs and measurement of the deflection dependent piezoresistive signal¹². While both approaches feature the advantage of direct integration on the MEMS component and as such provide a high potential for miniaturization, at the current stage, they do not provide sufficient accuracy for all applications. Thus in our devices *optical* position encoding was included.

2.2.1 Single axis

Optical position encoding can be implemented by measuring a laser beam reflected from the mirror with precisely positioned fast photodetectors as indicated in Fig. 2(a). In our device this is realized by using the reflection from the *backside* of the mirror die, which is freely accessible. In this way the position sensing unit is placed behind the MOEMS mirror and the front-side still is freely accessible for the optical applications. The angular position of the mirror is encoded by an optical trigger signal combined with a harmonic extrapolation function¹³. A fast photodiode at zero deflection angle allows accurate timing of the zero transition, which is crucial for a precise measurement of the phasedelay between the excitation signal and the mirror oscillation. This phase difference is a sensitive measure for the resonance frequency. Another diode, positioned at a well defined deflection angle can be used to determine the oscillation amplitude.

Fig. 2. (a) Scheme of the optical position sensing principle: The beam from a red laser diode module (LM) is reflected at the backside of the MOEMS mirror. Two fast photodetectors Det0 and Det1 measure the timing of the passage at the zero position and at a fixed angular deflection, respectively, which completely determines the angular movement within the harmonic approximation. Inset shows the line projected by a 1D device. (see text for details) (b) Relevant signals: from top to bottom: mirror deflection angle; rectangular driving signal at twice the mirror frequency; the signals from the photodiodes.

Fig. 2(b) shows the timing of the diode signals with respect to the mirror oscillation and the driving signal. As outlined below, the signals from the photodiodes, allow determining the angular movement within the harmonic approximation. This approach assumes harmonic motion of the MEMS scanners. It was verified, that the deviation of the mirror deflection from a pure sinusoidal motion is less than 0.1%.

This approach was successfully implemented for the case of 1D scanner mirrors⁷. In our 1D-device, shown in Fig. 6(a), which has a size of only $\sim 1\text{cm}^3$, the timing is measured and controlled with a precision of $<10\text{ ns}$ (corresponding to a phase difference of 0.01°).

2.2.2 2D-MEMS

Extending the same approach to 2D MOEMS devices implies a significant increase in complexity, because we have to characterize a 2D Lissajous figure instead of a straight line. For each axis we use a cylindrical mirror, in order to suppress the deflection of the orthogonal dimension. The principle is illustrated in Fig. 3.

Fig. 3: Basic scheme of the optical layout in the 2D device, which consists of the MEMS mirror (red) and two crossed cylindrical mirrors (large grey surfaces), which steer the beams to the corresponding detectors (blue rectangles) (Some beam-steering mirrors are not shown). The first inset shows the situation, where the MEMS mirror is tilted around one axis. As a consequence the beams are deflected, but the (vertical) deflection of the blue beam is compensated and there is no displacement on the detector. The other insets show the positions on the rectangular surfaces for all combinations of MEMS deflection angles around the two axes for $-4, 0, +4^\circ$.

Mirror deflection around one axis is compensated at the plane of the detection diodes while deflection around the other axis leads to a horizontal displacement of the beam. This reduces the problem to the control of a single 1D-oscillation and allows accurate position sensing and closed loop control for this axis.

Strictly speaking the compensation of the oscillation with cylindrical optics is not perfect. Geometrically elliptical mirrors, which project light from one focus to another, would be more exact. However, they are more difficult to fabricate and in simulations it was shown, that they do not provide a large improvement for the deflection angles under consideration. Furthermore, exact compensation of the deflection of one axis is only provided at zero deflection of the other, because of the projection of the beam onto a planar surface. This results in a small variation of the timing of the amplitude diode as a function of the deflection around the orthogonal axis, as can be seen in Fig. 3. It could be compensated by placing the two diodes on a curved surface, which, however, was not realizable in our small module, where we have to keep complexity at an acceptable level. In the device firmware this problem is reduced by averaging over a large number of measurements, which provides enough accuracy for amplitude control. There is no problem for the zero deflection diodes, which are hit at zero deflection and thus provide an accurate timing signal independent on the other axis.

2.3 Control Concept

2.3.1 Amplitude and Phase of the individual axes

The control scheme of amplitude and phase in the 1D-mirror device was described in much detail previously⁸. In short the phasedelay pd , defined as the delay between the falling edge of the driving voltage and the zero-crossing of the mirror, is determined. The phase φ , expressed in degrees, is given by $\varphi = \frac{pd}{T} 360^\circ$, where $T = \frac{1}{f}$ is the period of the mirror oscillation. By adjusting the frequency f in order to minimize this delay, operation at resonance can be obtained. Furthermore, by measuring the delay between successive zero crossings, small misalignments of positioning of the trigger diode, can be corrected⁸. The amplitude can most conveniently be determined by measuring the delay t_A between two successive trigger pulses from the amplitude diode and using $A = \frac{X_0}{\sin(\pi(\frac{1}{2} - \frac{t_A}{T}))}$, where X_0 is the known position of the amplitude diode.

Fig. 4 provides an overview of the interdependencies in our control concept. In fully controlled mode, we continuously adjust the frequency for minimal phasedelay, which assures operation at resonance, and then adjust the driving voltage to keep the amplitude constant. Since the phase dependence on driving voltage is rather small, this scheme converges quickly and provides stable operation.

Fig. 4: (a) Phasedelay as a function of frequency for a fixed driving voltage of 100 V. (b) Phasedelay as a function of driving voltage for a fixed driving frequency of 45.85 kHz. (c) Amplitude as a function of frequency. (d) Amplitude as a function of driving voltage.

2.3.2 Relative phase in a 2D scanner

For the projection of a stable Lissajous pattern the control of the phase between the two axes is crucial⁶. To determine the relative phase in our device, we measure the timing between the zero crossings of the two axes. Basically, we measure the delay between the zero crossing of the slow (y-) axis and the subsequent zero crossing of the fast (x-) axis.

The situation is somewhat complicated by the fact, that (except for the case that f_x is an integer multiple of f_y) we have multiple zero crossings of the slow axis, before the Lissajous-figure repeats itself, as is outlined in Fig. 5 for the simple

case of a frequency ratio of $f_x/f_y=5/3$. A more detailed mathematical description is presented elsewhere¹⁴ and for this experimental article we just state, that these delays are measured and analyzed in order to keep the relative phase between the two oscillations at a constant well defined value. In general, in order to obtain a symmetric Lissajous pattern, the value will be $\Phi=0$ if v_x or v_y is a pair number and $\Phi=\pi/2$ if both, v_x and v_y , are impair⁶.

Fig. 5: Scheme of the relevant signals for the Lissajous Phase for the case of a 2D-mirror with $f_x=5$ kHz and $f_y=4$ kHz: From top to bottom we show the sinusoidal mirror deflection for each axis and the corresponding signal obtained from the triggerdiode. (In the scheme, the trigger pulses are connected by dotted lines, in order to more clearly distinguish the rising/falling edge) The delays between the slow axis zero-crossing and the next fast axis zero-crossing (rising edge only), which are measured in the device are indicated.

In closed loop operation, the relative phase in our device is controlled continuously and, if necessary adjusted by adapting the frequency of the slow axis. In this way, the fast axis, which is more critical, can still be operated at resonance in all cases, while the frequency of the slow axis now is controlled with goal of achieving a stable relative phase, instead of operation at resonance.

3. SYSTEM INTEGRATION

Since it was partially presented otherwise¹⁵ we will only give a short outline of the basic components of our devices with a special focus on the electronics part, which have not been described, yet, for the 2D module.

3.1 MOEMS device

All micromechanical scanner mirrors were fabricated at the IPMS. The devices are designed to accept mirrors in the range from 200 Hz up to 25 kHz. The resonance frequency of the MOEMS 1D scanners used in this work is around 23 kHz. The 2D-MOEMS mirrors have a resonance frequency of $f_x=1,3$ kHz and $f_y=200$ Hz.

The driving voltage can be in the range from 20-180 V. In this work, the 1D mirrors were typically driven in the range of 80 up to a maximum of 180 V and the 2D-mirrors at voltages between 20-50 V. Mechanicals amplitudes in the range of 10° can be obtained with these mirrors. The front side of the mirror is coated with aluminum to enhance the reflectivity. The backside, which is used for the position detection in our device, is a silicon surface. The mirror area was 1 mm^2 .

3.2 Detector head

Fig. 6. Photo of the (a) 1D-device and (b) 2D device

Shortly the 1D module consists of four parts (c.f. Fig. 6(a)): (i) A mechanical baseplate, which includes the geometry to send the beam from a laser module onto the backside of the mirror and target the reflected beam towards the photodiodes. (ii) The sensor electronics board with the two photodiodes and the laser module, which was connected to the main electronics board with a flexprint cable. (iii) the MEMS board on which the MEMS mirror is fixed and electrically bonded. It is connected to the sensor board via hot bar soldering. (iv) The frontoptics, which consist basically of an optical half dome, in order to provide hermetic sealing. The size of the final position sensing device, where the MEMS mirror is integrated, is $20 \times 14 \times 6 \text{ mm}^3$ and the control board which comprises all electronics for autonomous control of the mirrors has a size of $45 \times 75 \text{ mm}^2$.

The parallel beam of a miniaturized laser module was directly sent to the mirror and subsequently to two differential photodiodes (Hamamtsu, S9684). Using a folded geometry we could realize a distance of ca. 2 cm between the scanner mirror and the photo detectors.

The 2D modules are significantly more complex. The mechanical baseplate now consists of two parts. The upper part responsible for the beam delivery contains two laser modules in order to provide two beams from orthogonal directions to the backside of the mirror. The beams hit the mirror with an angle of incidence of 30° . A steeper angle of incidence, as realized in the 1D module, is not possible here, because the two beams must be geometrically separated afterwards, when they are collected by the cylindrical mirrors. The latter are included in the lower part of the baseplate which contains the position detection pathway. However, this angle of incidence, in combination with the limited aperture of the MEMS mirror backside, limits the maximum deflection angles before clipping occurs. Another restriction stems from the limited size of the cylindrical mirrors which have to be hit.

The optical surfaces in the 2D module are aluminum mirrors, which are glued onto the baseplate. Due to the complexity of the unit, it was not possible any more, to directly polish the optical surfaces, as was done in the 1D module. The four photodiodes are positioned on a sensor PCB board, which is wrapped around the module. The distance between the mirror and the photodiodes is about 2 cm, which allows for very similar timing characteristics as obtained in the 1D board. The 2D Module has a size of ca. $20 \times 15 \times 15 \text{ mm}^3$. The sensor head is connected via a ribbon cable with the main electronics.

Front-optic and MEMS-board are identically to the 1D module. Currently the front optic is glued to the PCB board. Using a ceramic board and soldering techniques, vacuum tight hermetic packaging is possible. This could further improve the mirror performance allowing even larger deflection angles or lower driving voltages. The half dome has a certain refractive power, depending on thickness and glass, which has to be considered, when designing an optical application with the module.

3.3 Electronics

The module itself, as shown in Fig. 6 comprises the optics module, together with the MEMS component, the trigger diodes, and the laser module. It is connected to the control electronics board via a flexprint-cable (c.f. Fig. 7). The electronics concept is shown in Fig. 8.

The central core is a DSP-PIC microcontroller, which deals with the mirror driver, all communication, averaging, and data processing. It has to ensure the start-up and the control of the MEMS mirror. This micro-chip DSP microcontroller

(dsPIC33FJ256GP710) has 85 universal inputs / outputs which allows recording all the necessary mirror parameters. Furthermore, an EEPROM for storing the mirror parameters is provided. If a mirror is connected to the control electronics module, then the associated mirror and operation parameters are retrieved.

Fig. 7: electronic main boards for (a) 1D- and (b) 2D-MEMS devices.

Accurate frequency generation was performed with a direct digital synthesizer IC. For the high-voltage generation of a HV converter Q02-5 from Hivolt is used. This component is extremely small and measures only $12.7 \times 12.7 \times 12.7 \text{ mm}^3$. At a control voltage between 0.7 V and 5 V it generates output voltages between 12 and 200 V. Including a certain tolerance this implies that the minimum driving voltage level is $\sim 20 \text{ V}$. However, on the other side limitations arise from the HV DC voltage, which must be generated by rectangular voltage switching transistors. For this purpose, an additional half-bridge driver of the type L6384 is used. It must be noted that this part of the circuit requires relatively much space because of the high voltage components, which are necessary.

Two identical HV-voltage modules are used to provide two independent power supplies for the axes. The control is carried out over an external ADC, which is programmed via the SPI bus from the dsPIC.

Furthermore the DSP must read in and evaluate the timing signals from the optics module. For this purpose, the signals from the photodiodes are preprocessed in a CPLD (X2C64A by Xilinx), to produce clean rectangular signals, which were measured with ps-temporal resolution using time-to-digital converters. In addition, the driving signal was frequency divided by two in the CPLD, to provide a reference signal with the same frequency as the mirror oscillation. In principle, it should be possible to multiplex the signals to a single TDC on the board using combinatorial logic in the CPLD. As a result, the space requirement on the control board would be further reduced. In the first hardware version, this has not been implemented, yet.

Fig. 8: Scheme of the electronic concept

The sensor electronics for each mirror axis consist of two differential photodiodes (S9684 from Hamamatsu). A small laser module (APCD-650-06-C2-A) is used to generate the beam. In the case of the 2D device two laser modules were included. The sensors provide digital output signals and are arranged on the PCB in order to detect the zero-passage and the passage at a defined amplitude deflection. In closed loop operation, position control for each of the two mirror axes is provided by two optical sensors in the 1D module and 4 sensors in the 2D module. The timing between the signals must be measured with high accuracy, which cannot be provided by the clock rate of the DSP controller. It is therefore

necessary to use a time-to-digital converter of the type TDC-GP2 from Acam. This component has a size of only 5x5 mm² and a temporal resolution of 65 ps.

The controller reads out the data via the SPI interface and then calculates the amplitude and phasedelay of each axis. The phase between the oscillations of the x-and y-axis in the 2D device is measured with an additional TDC, which takes as a start input the zero-crossing of the slow frequency oscillation and as a stop signal the zero crossing signal of the fast axis. The DSP then adjusts the control parameters of the axis, so that a well-defined Lissajous figure can be generated.

The results can be retrieved on a PC connected via a serial interface.

4. EXPERIMENTS AND RESULTS

4.1 Longterm stability

Due to environmental influences, when driven with a fixed voltage at a given constant frequency (open loop mode) the MOEMS devices show significant drifts in amplitude and resonance frequency on the timescale of minutes. In closed loop operation, the shown device actively controls the phase between mirror motion and driving frequency to work close to the resonance with constant amplitude at any given time. Additionally, the amplitude is kept constant by adjusting the voltage.

The results below demonstrate the capabilities of the 1D and the 2D device. Fig. 9 shows first experimental results concerning the long term stability of the devices.

Fig. 9(I) displays the results of monitoring amplitude and phasedelay of a 1D-scanner mirror over time with and without closed loop control. In the open loop situation, the mirror was driven with a constant voltage and at a fixed frequency. Due to environmental influences the mirror motion shows a significant drift over time. In closed loop operation, this drift can be completely compensated, albeit with a slight increase in high frequency noise. This drift-compensation was also demonstrated under temperature variation for the 1D device [8]

Fig. 9: (I) Measurements of Amplitude and Phasedelay in our 1D-device under normal working conditions. With closed loop control Amplitude (a) and Phase (c) are kept constant, while they show a significant drift in open loop on a timescale of minutes (b), (d). (II) (a) Phasedelay, (b) amplitude of the fast axis and (c) the relative phase in the 2D-device under normal working conditions.

First results with the 2D device are shown in Fig. 9(II). The phasedelay and amplitude of the fast axis are displayed, as well as the relative phase between the two axes. In open loop operation, each axis is driven at a given fixed frequency. The driving frequencies are generated at two independent DDSs and thus are not exactly synchronized, which leads to a linear drift in the relative phase. Stabilization of amplitude and phase of the individual axis in closed loop operation works similar to the 1D situation and is demonstrated in Fig. 9(IIa,b). In addition, in closed loop operation, the relative phase is kept constant by adjusting the slow axis frequency. This approach ensures stable projection of a Lissajous pattern. Phase stability of better than 0.5% was obtained in our first tests.

4.2 Short term fluctuations

In addition we characterized the short time behavior of the 2D MEMS device. For this purpose we used a laser beam which was reflected from the front-side of the MEMS device and measured its position with a position sensitive photodiode (PSD). The PSD signal was recorded with an oscilloscope, which allowed complete analysis of the mirror motion. This provides additional information, compared to the backside measurements of the device, because in this case, the whole trajectory is recorded on the oscilloscope in contrast to timing signals from the photodiodes used in our device.

Fig. 10: X- and Y- signal from the PSD: (a) individual traces, (b) plot y vs x (see text for details)

Fig. 10 shows typical data. The frequencies were set to 1250 Hz and 187 Hz. In order to investigate the short time jitter of the mirror oscillations in our device, we typically registered a long trace, limited only by the buffer of our data acquisition card. This trace was broken down into a series of frames containing three slow axis periods each. For each frame the current frequency and the relative phase of the slow and the fast axis were determined. The results are shown in Fig. 11, where open loop and closed loop situation are compared on short timescales.

Fig. 11: Phase difference between fast and slow axis in radians. (a) open loop situation and (b) phase locked case

We see that in open loop, the relative phase drifts away, because the frequencies of the two axes are not synchronized. On the other hand, this is compensated by our closed loop control. In this case, for the purpose of demonstration, we set the boundary values for the control rather large, causing the relative phase to oscillate between these phase delay values. Optimization of the control parameters is currently ongoing.

At the current stage we directly used the position information of the PSD. More detailed analysis should include the facts that the incoming beam is tilted with regard to the mirror normal and that the outgoing beam is projected onto a flat

surface, as well as other experimental details. Such an analysis could also reveal deviations from purely sinusoidal motion. At this stage of the experiments it can already be said, that this deviation is less than 0,1%. In depth analysis and a detailed description of our test-stand will be presented elsewhere.

5. CONCLUSIONS

In this article we presented a novel unit for closed-loop control of electrostatically driven 2D-MOEMS mirrors which will significantly improve the performance of these components. We presented the principles of our position encoding scheme, focused in much detail on the realization and the particularities of the 2D mirror device. The first experimental results prove the feasibility of our phase-locking concept and demonstrate the abilities of our device. In depth characterization of the 2D device is currently ongoing.

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